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Canted-Undulator Front-End Exit-Mask Flow-Induced Vibration Measurements

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Abstract

All of the high-heat-load critical components in the new canted-undulator front-end (CU FE) design use wire-coil inserts inside of the cooling channels to significantly enhance heat transfer. Wire-coil inserts have replaced the copper-mesh inserts used in previous front-end high-heat-load critical-component designs. The exit mask, the most downstream component in the CU FE line relative to the x-ray beam path, has an exit aperture of 2 mm vertical x 3 mm horizontal and is the most sensitive component, in terms of final beam stability, of all of the CU FE components. In general, final beam stability is determined by the storage-ring output-beam stability and not by the CU FE components. Although front-end components are not very sensitive to vibration, several measurements have been performed to assess the flow-induced vibration associated with the CU FE exit mask. Results yield only 0.16 µmrms vertical displacement and 1.0 µmrms horizontal displacement under worst-case conditions. The maximum displacement values are very small compared to the aperture size, and therefore flow-induced vibration has a negligible effect on the CU FE output beam stability.

More general measurements have also been performed to directly compare flow-induced vibration in an open, unrestricted tube relative to the same tube containing either a wire-coil insert or a copper-mesh insert. Operational performance data are presented for these heat-transfer-enhancing inserts, and the advantages and disadvantages, in terms of selection criteria, are discussed.

1. Introduction

All of the Advanced Photon Source (APS) front ends contain a series of components designed to either aperture or completely stop the powerful APS x-ray beam. The new canted undulator front end (CU FE) receives on the order of three times more total power than previous generation APS front ends with 20.4 kW of total power and 281 kW/mrad^2 of peak power density delivering a maximum normal-incidence heat flux of around 1100 W/mm^2. In order to meet the high-heat-load/flux demands, all of the critical components contained within the CU FE use wire-coil inserts inside of the cooling channels to significantly enhance heat transfer. Although final beam stability is, in general, determined by the storage-ring output-beam stability and not by front end (FE) components, several measurements have been performed to assess the flow-induced vibration associated with the CU FE exit mask. Front end components are not very sensitive to vibration; however, the exit mask, with an exit aperture of 2 mm vertical x 3 mm horizontal, is the most sensitive in terms of final beam stability because it is the most downstream component in the CU FE line relative to the x-ray beam path and has the smallest aperture.

Previous generation FE designs used copper-mesh inserts instead of wire-coil inserts to significantly increase heat transfer. In addition to the vibration measurements performed on the CU FE exit mask, more general measurements have also been performed to directly compare flow-induced vibration in a plain, unrestricted tube relative to the same tube containing either a wire-coil insert or a copper-mesh insert Comparison is made on the basis of equivalent flow rates. These data compliment the existing pressure-loss and heat-transfer-performance data previously compiled for these heat-transfer-enhancing inserts [1-2]. Operational performance data are presented for these inserts, and the merits, in terms of selection criteria, are discussed.

2. Experimental Results

All data presented in this paper were acquired using an HP 35670A dynamic signal analyzer (DSA). Model number 393B31 accelerometers made by PCB were used to measure the vibration. These accelerometers have a sensitivity of 10 V/g.

An operational CU FE exit mask was instrumented with accelerometers in both the vertical and horizontal planes in order to capture both vibration modes. After installation, sufficient time was allowed for the accelerometers to settle prior to experimentation. Instead of only capturing data at the operating flow rate, data were collected in increments across the flow range including a measurement with zero flow in order to establish background vibration.

The CU FE exit mask contains eight wire-coil inserts, four under the top beam-strike surface and four under the bottom beam-strike surface. The channels for the top and bottom beam-strike surfaces are supplied cooling water in parallel, with the top and bottom channels connected in series. Therefore, for this component, the flow rate per cooling channel is the total component flow rate divided by four. It should also be noted that displacement results are discussed in terms of microns rms but most of the plots contained in this paper are displayed in terms of nanometers rms for ease of readability.

Figures 1 and 2 present the vertical and horizontal displacement as a function of flow rate and frequency, respectively. For reprints of this paper where color is not available, the data presented in Figures 1 and 2 are provided in the Appendices with one plot for each flow

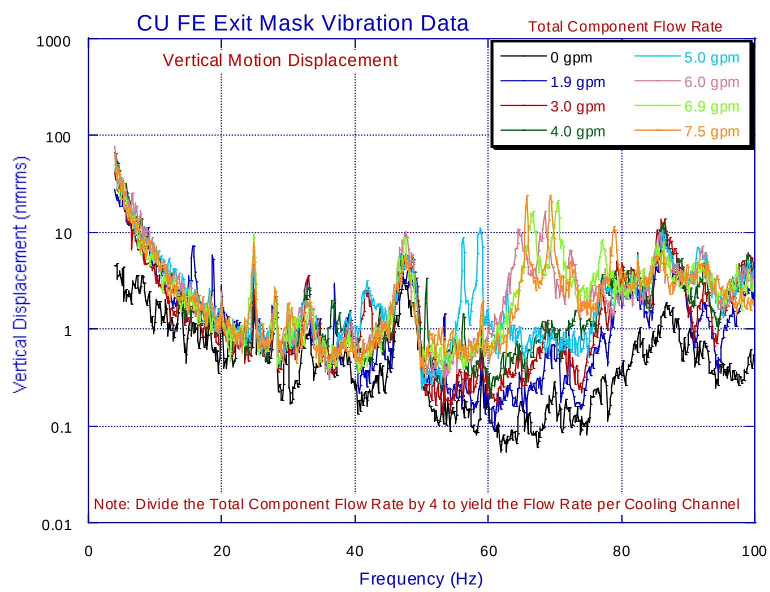

Figure 1-Vertical Displacement as a function of Frequency. See color key for flow rate. Refer to Appendix A.

rate. Refer to Appendix A and B for the vertical and horizontal displacement data, respectively. The vertical displacement is on the order of 0.1 μmrms and the horizontal displacement is on the order of 1.0 μmrms. Corresponding to these data, vertical and horizontal motion-band power is plotted as a function of flow rate in Figures 3 and 4, respectively. Motion-band power refers to the summation of the displacements integrated across the frequency range. The shape of these curves is interesting in that there is a definite peak in both cases, though more pronounced for the horizontal band power. The vertical band power curve is nearly linear up to 4 gpm and peaks at around 0.16 μmrms at a total component flow rate of 6.0 gpm. At higher flow rates, the vertical band power seems to decrease slightly and then level off. A sharp peak occurs on the horizontal band-power curve at just over 1.0 μmrms at a total component flow rate of around 7.0 gpm; however, at higher flow rates, the horizontal band power sharply decreases and does not seem to level off as was the case with the vertical band power. Flow-induced vibration seems to contribute very little relative to the background up to 3 gpm in terms of the horizontal motion band power. It is apparent that vertical band power is much more affected by flow-induced vibration than horizontal band power; however, the magnitude of the horizontal band power is nearly ten times that of the vertical band power.

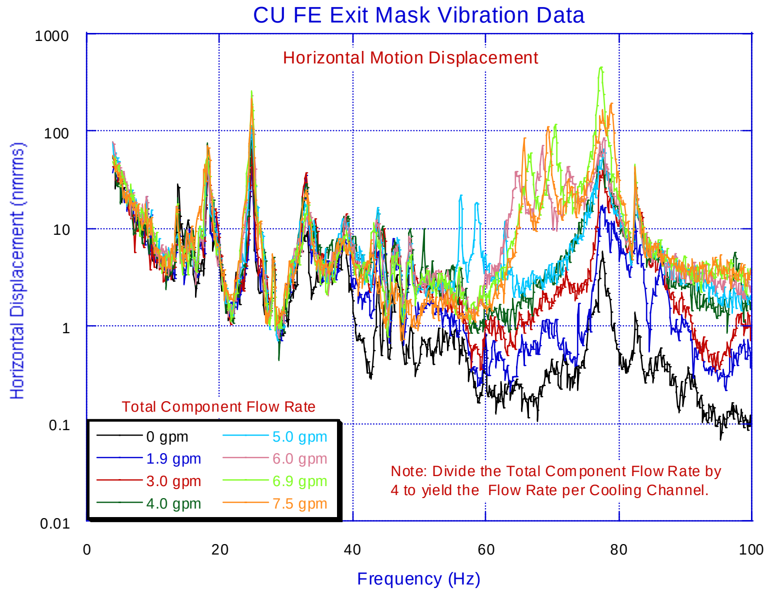

Figure 2-Horizontal Displacement as a function of Frequency. See color key for flow rate. Refer to Appendix B.

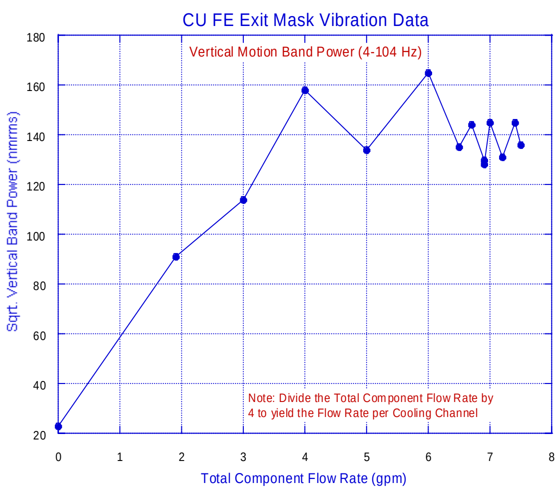

Figure 3-Vertical Band Power versus Flow Rate

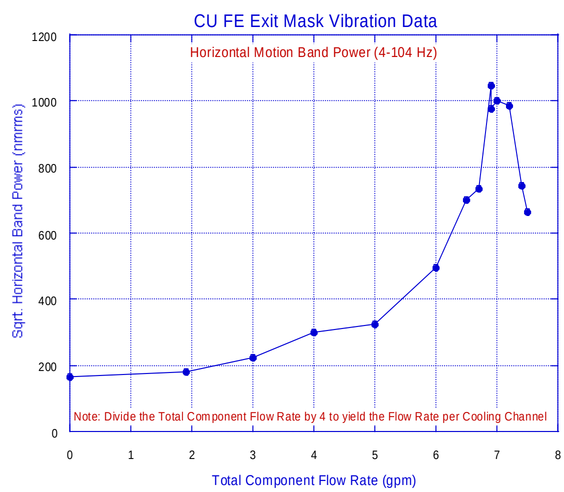

Figure 4-Horizontal Band Power versus Flow Rate

About a month before the data presented above were taken, the vertical motion of a different CU FE exit mask was measured at the operating flow rate of 7.5 gpm during a brief access period, and the results were internally distributed. Unfortunately, although the results yield tolerable vibration levels with a displacement band power of 2.58 μmrms, the data below 50 Hz are suspected to be erroneously high due to insufficient settling time for the accelerometer. The data plot that was initially distributed is presented in Figure 5.

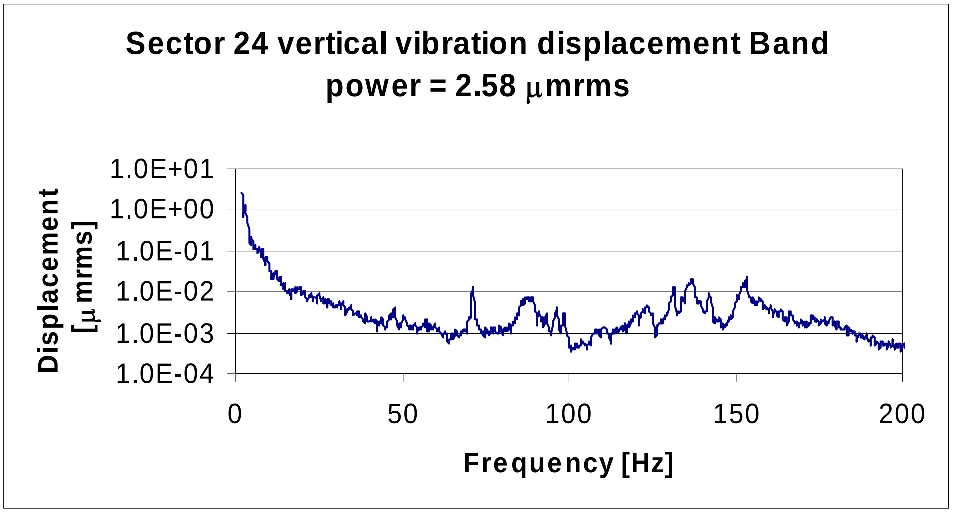

Figure 5-Vertical Band Power as a function of Frequency.

For comparison, Figure 6 presents these initial erroneous vertical displacement results with the later measurements from Figure 1 at an operating flow rate of 7.5 gpm. The data are nearly identical above 50 Hz thus verifying that the behavior of the two exit masks is very similar. It is also evident that the erroneously high data below 50 Hz in the original measurement had a huge impact on the band power considering that there is nearly a 20-fold difference between the two band-power values.

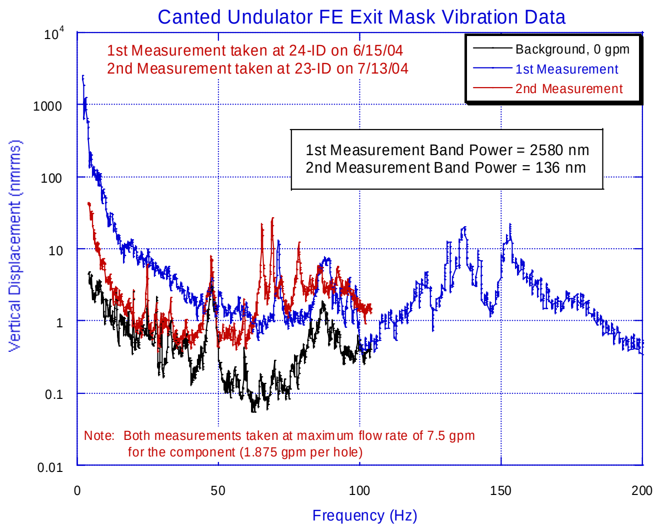

Figure 6-Vertical Displacement as a function of Frequency

In addition to the vibration measurements made on the CU FE exit masks, a laboratory test section was created in order to directly compare vibration levels as a function of flow rate for a plain, unrestricted channel relative to the same channel containing either a wire-coil insert or a copper-mesh insert. The specific displacement values in the measurements are not important, in fact, the mass of the system was minimized in order to amplify the displacement values for better resolution. A 2 in x 2 in x 1 in high plate, used to mount an accelerometer, was brazed onto the center of a single 24 in long 1/2 in OD, 3/8 in ID copper tube. The tube was supported at both ends by rigid couplings connected to a regulated water delivery system, and the tube was suspended in space to allow undampened vibration. With no inserts installed, the tube was initially tested, recording displacement versus frequency, across the flow range. Next, the tube was retested in the same manner, first with a copper-mesh insert and then again with a wire-coil insert installed inside of the tube. This allows for a direct comparison of displacement as a function of flow rate for the plain tube relative to the same tube containing either a wire-coil insert or a copper-mesh insert.

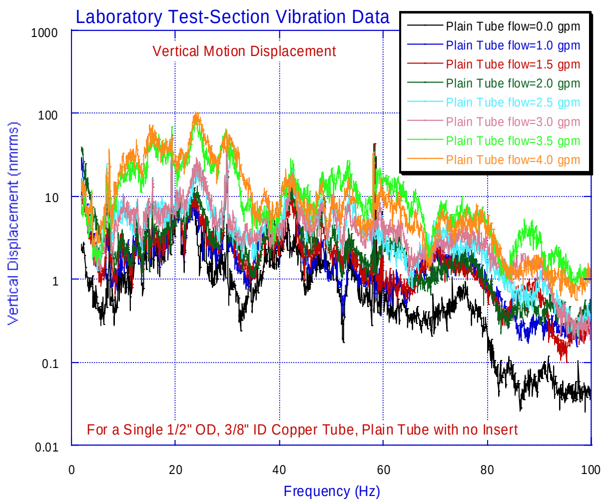

Figure 7-Vertical Displacement as a function of Frequency for the Plain Tube. Refer to Appendix C.

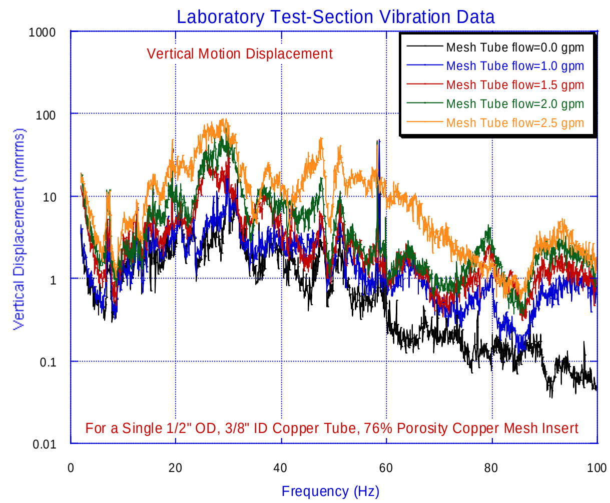

Figure 8-Vertical Displacement as a function of Frequency for the Mesh-Insert Tube. Refer to Appendix D.

Figures 7, 8 and 9 present the vertical displacement as a function of frequency and flow rate for the plain, unrestricted tube, copper-mesh-insert tube, and the wire-coil-insert tube, respectively. Again, the data presented in Figures 7, 8 and 9 are provided in the Appendices with one plot for each flow rate. Refer to Appendix C, D and E for the plain tube, copper-mesh-insert tube, and wire-coil-insert tube vertical motion displacement data, respectively. It is interesting that, above 20 Hz or so, the displacement values are fairly similar for all three cases, not exceeding 0.1 μmrms, but below 20 Hz for the wire-coil-insert case the displacement

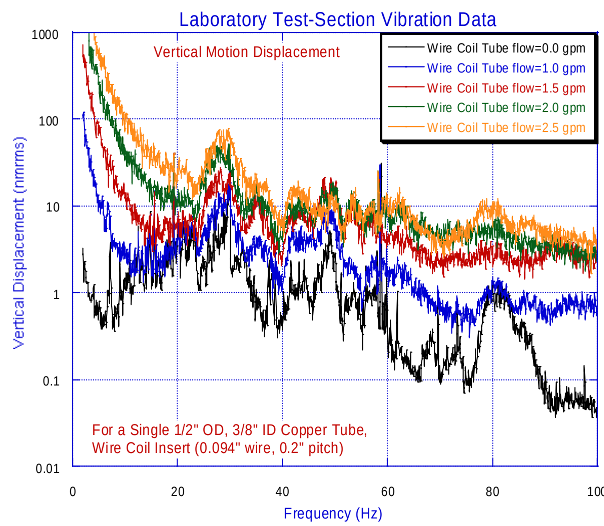

Figure 9-Vertical Displacement as a function of Frequency for the Wire-Coil-Insert Tube. Refer to Appendix E.

values increase significantly. The actual cause of the increase is unknown at this time, perhaps the geometry of the wire-coil insert creates resonance at low frequencies, but the data are believed to be valid.

Figure 10 presents the band power as a function of flow rate corresponding to the previous data for the plain tube, copper-mesh-insert tube and wire-coil-insert tube. Clearly the wire-coil insert introduces more vibration than the copper-mesh insert, but both create more vibration than the plain, unrestricted tube alone. The mesh-insert tube behaves nearly identically to the plain tube, in terms of motion band power, at flow rates less than 1 gpm. Most of the vibration associated with the wire-coil insert is generated at frequencies below 20 Hz, but this contribution adds significantly to the motion band power.

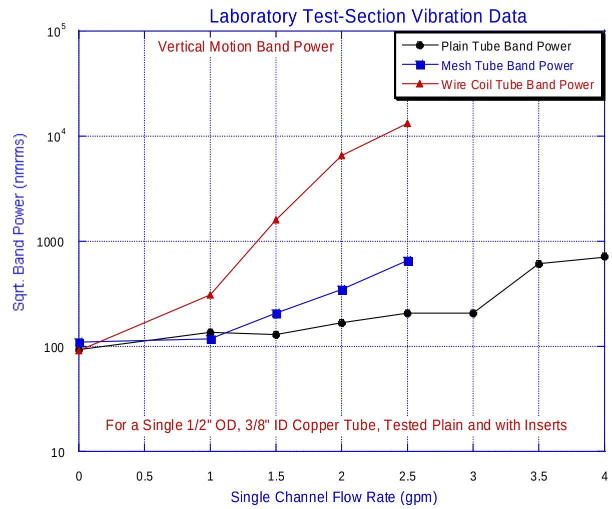

Figure 10-Vertical Band Power as a function of Flow Rate for laboratory test-section

3. Discussion

Although the wire-coil insert clearly introduces more vibration than the copper-mesh insert, one must keep in mind the reason why enhanced heat-transfer techniques are used in the first place. All FE high-heat-load/flux components require high-heat-transfer rates not available with plain, open cooling channels unless excessively high flow rates are used. Both the wire-coil insert and the copper-mesh insert increase the heat transfer rate on the order of 4- to 6-fold over a plain, open cooling channel operating at the same flow rate.

Figure 11 presents typical heat transfer data as a function of coolant flow rate comparing a plain, unrestricted tube to a copper-mesh insert and wire-coil inserts of various

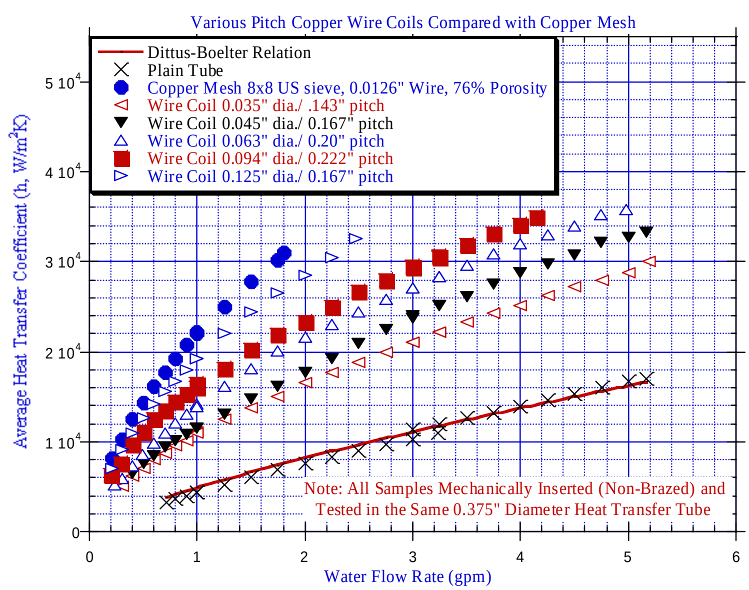

Figure 11-Heat Transfer Coefficient as a function of Water Flow Rate for various inserts relative to a plain tube

geometries. For all of the CU FE high-heat-load critical components, we have chosen an optimum wire-coil geometry using 0.094 in diameter wire with a pitch of 0.2 in. The data shown in Figure 11 for the 0.094 in diameter wire with a pitch of 0.222 in is very close to the data for our optimum coil. All previous generation FE high-heat-load critical components use 76% porosity copper-mesh inserts. All CU FE high-heat-load critical components have a design heat transfer coefficient of h=1.5 W/m^2K [3]. From Figure 11, the design heat-transfer coefficient can be achieved using either a copper-mesh insert at a flow rate of around 0.6 gpm or a wire-coil insert at a flow rate of just under 0.9 gpm; however, a flow rate of nearly 4.5 gpm would be required if only a plain, open channel were used. Referring back to Figure 10 and extrapolating the plain tube data out to 4.5 gpm, the vibration generated by this high flow rate would be greater than that of a wire-coil insert.

At first glance one might assume that the copper-mesh insert is the better choice since less coolant flow rate is required to achieve a certain level of heat transfer relative to the wire-coil insert. However, there are several problems with the copper-mesh insert. The first problem is that copper-mesh inserts produce very large pressure loss, thus limiting their usable length. Figure 12 presents the pressure loss per inch of insert length versus the coolant flow rate for the same data detailed in Figure 11. The pressure loss per inch of insert length is excessive for the mesh insert. For the design heat-transfer coefficient h=1.5 W/m^2K, the pressure loss for the copper-mesh insert is around 2.0 psid/inch, whereas, for the wire-coil insert, the pressure loss is only 0.25 psid/inch. All of the CU FE high-heat-load critical components tend to be longer with shallower grazing-incidence angles than previous generation designs due to the greatly increased heat flux/load requirements. Copper mesh could only be used in the CU FE designs if all cooling passages were supplied cooling water in parallel and consequently the resulting operating flow rates would be greater than that required for the present designs that use wire-coil inserts.

This alone may not detract from the use of copper-mesh inserts, considering that the flow-induced vibration is lower; however, the main problem with the use of copper-mesh inserts is that they can be maintenance intensive. All components that contain copper-mesh inserts must have their cooling water supply meticulously filtered and maintained for quality. Typically, components that contain copper-mesh inserts must

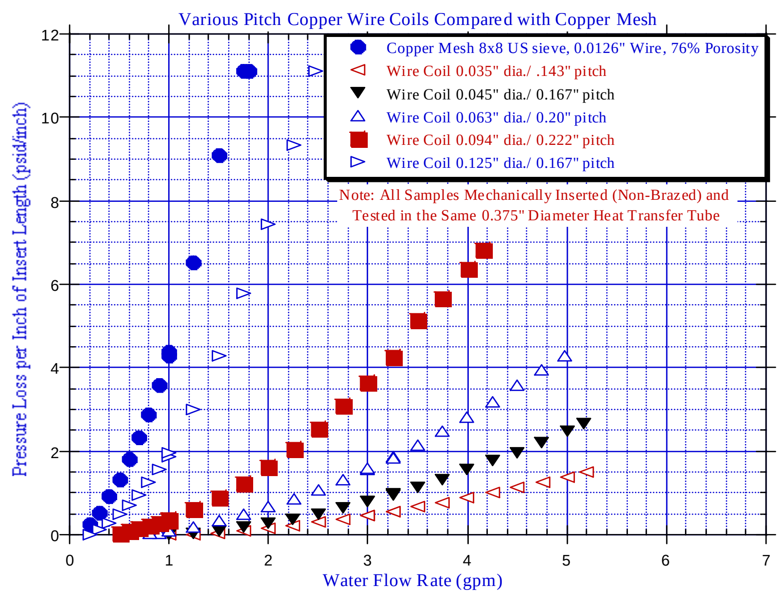

Figure 12-Pressure Loss as a function of Water Flow Rate for various inserts

be Citranox cleaned on a yearly basis due to fouling. In addition, due to the small 0.0126-in wire size used in the copper mesh inserts, long-term erosion is a concern. Finally, in all of the previous FE high-heat-load component designs, the copper-mesh inserts had to be brazed inside of the cooling passages for proper operation, and this added considerably to the manufacturing process.

Wire-coil inserts, on the other hand, are robust due to the large 0.094 in wire size and are unlikely to ever clog or foul even if the water quality is not well maintained. Wire-coil inserts are easily manufactured and do not require brazing. From a maintenance and manufacturing standpoint, wire-coil inserts are a vast improvement over copper-mesh inserts.

Note that, the use of wire-coil inserts to increase heat transfer was unknown at the time when previous FE high-heat-load designs were being considered. The previous designs used the best technology available to meet the high-heat-load/flux requirements, the copper-mesh insert being far superior to anything else available at the time. Many of the original FE high-heat-load components have been in service for over ten years and will continue to provide reliable service for many years to come.

4. Conclusion

Although wire-coil inserts generate higher levels of flow-induced vibration than their predecessors, copper-mesh inserts, the levels of vibration generated are quite tolerable for all CU FE high-heat-load component applications. The exit mask, the most sensitive component in the CU FE in terms of beam stability, yields only 0.1 μmrms vertical displacement and 1.0 μmrms horizontal displacement at the maximum operating flow rate. The maximum displacement values are very small compared to the 2 mm vertical x 3 mm horizontal exit-mask aperture, and therefore the flow-induced vibration has negligible effect on the CU FE output beam stability. For extremely beam-stability-sensitive devices, such as slits with optical knife-edges, depending on the heat transfer requirements, the flow rate can be reduced to significantly lower the flow-induced vibration effects. All things considered, wire-coil inserts are a superior choice for most high-heat-load component applications.

5. Acknowledgment

The authors thank Emil Trakhtenberg, chief design engineer for the CU FE, for initiating this work. The authors also thank the staff at APS Sectors 23 and 24 for allowing vibration measurements to be performed on their exit masks. Thanks are also given to S. Picologlou for editing this paper. This work was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.

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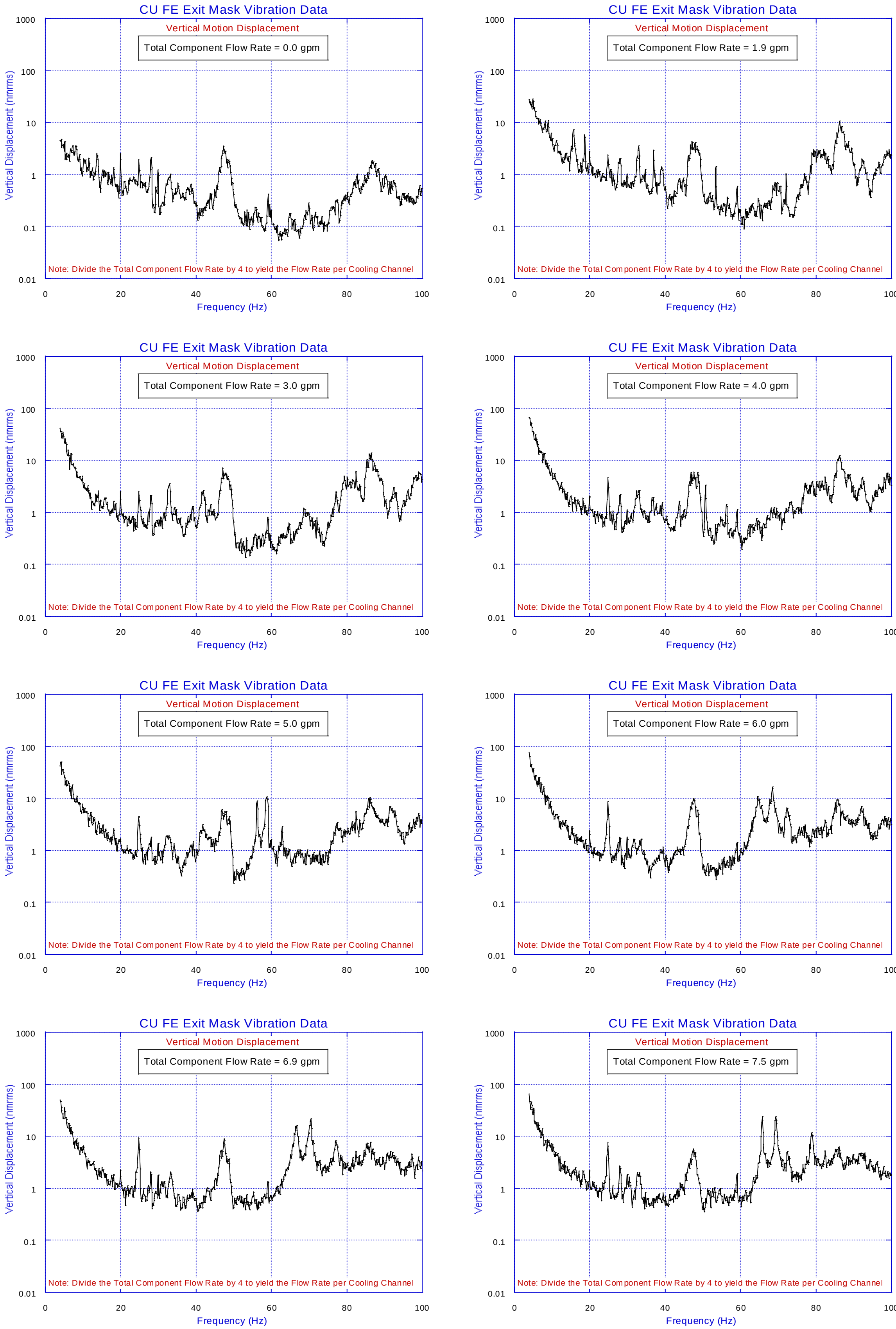
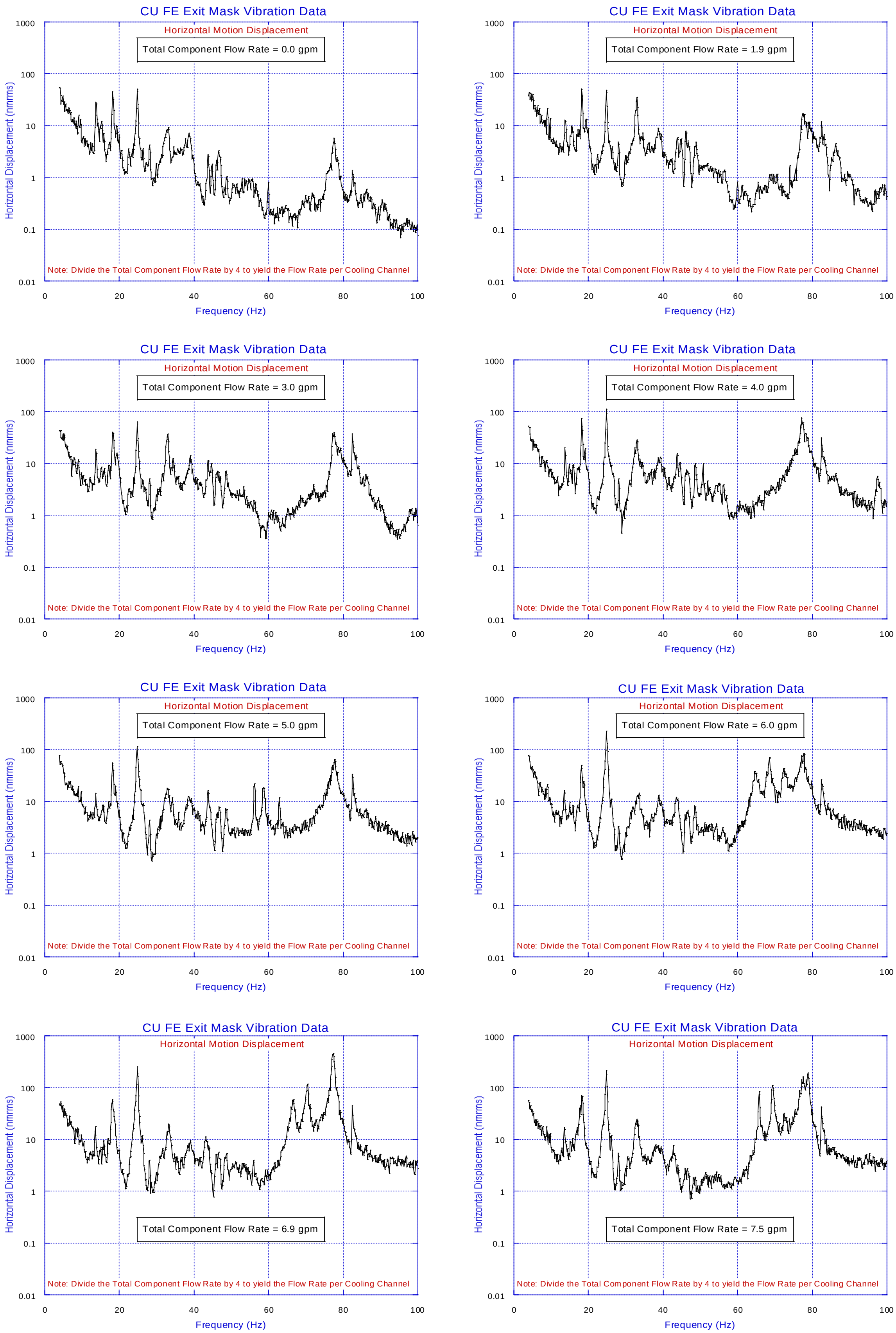
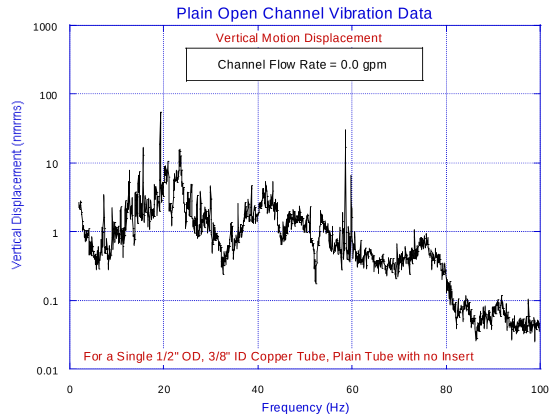
Appendices

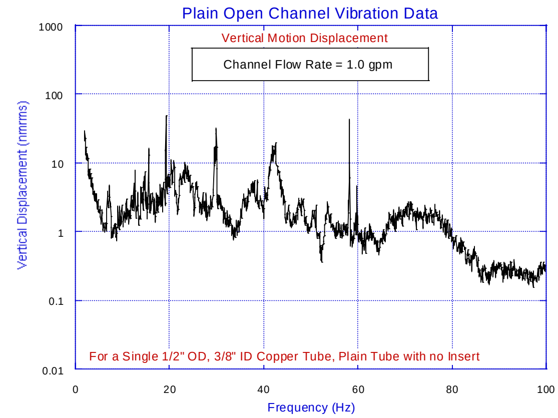


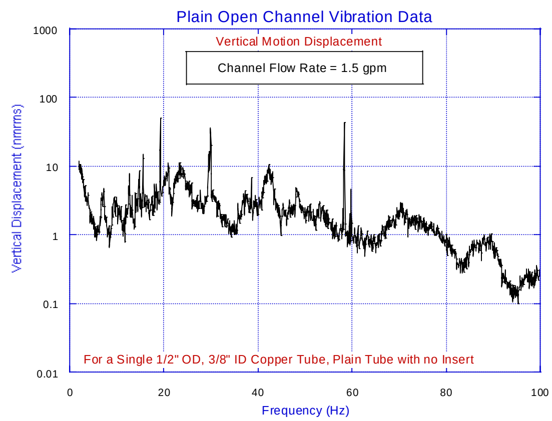
Appendix A : CU FE Exit-Mask Vertical-Motion Displacement

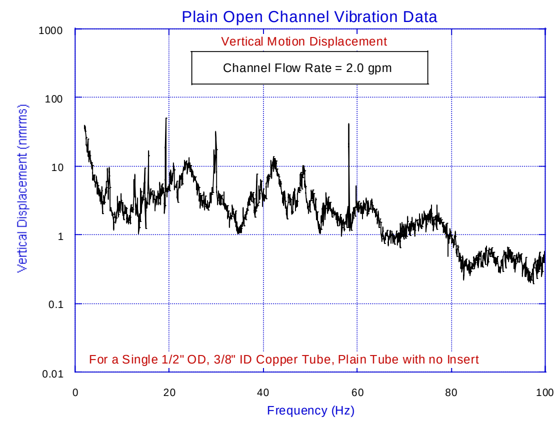


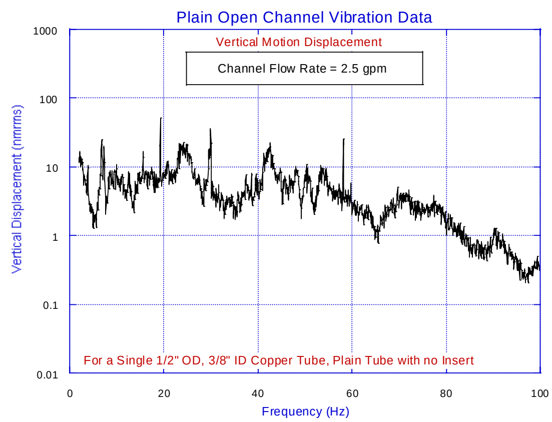
Appendix B : CU FE Exit-Mask Horizontal-Motion Displacement

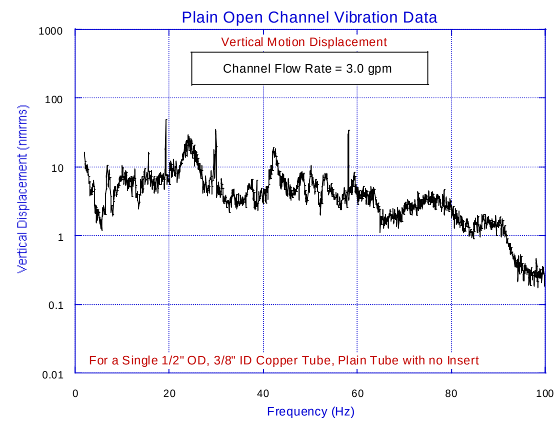


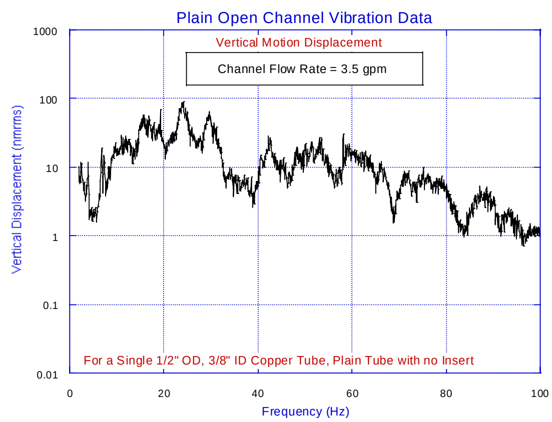


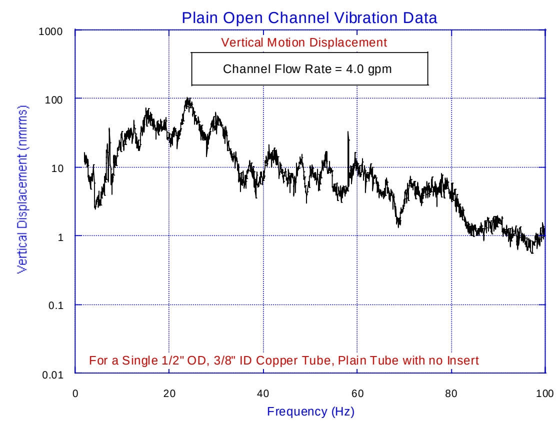




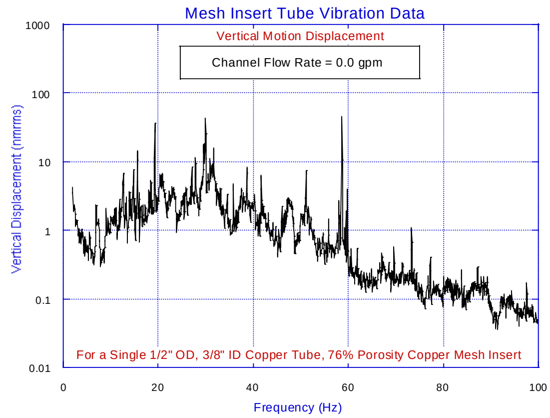


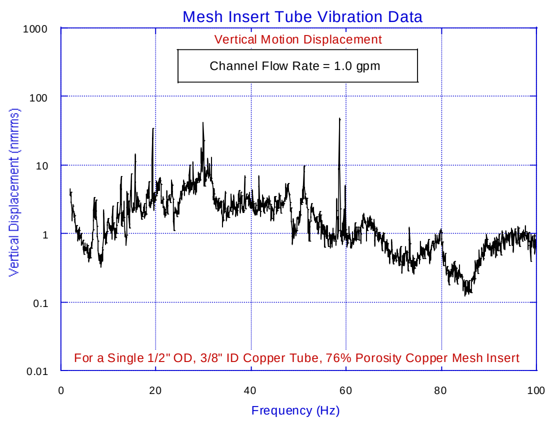


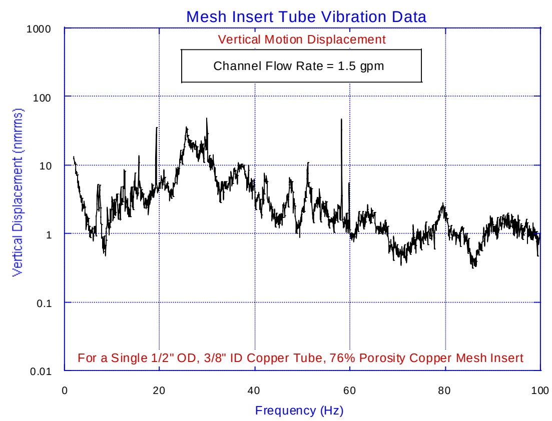


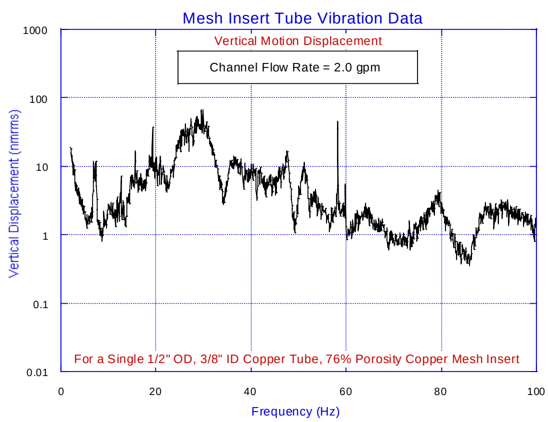


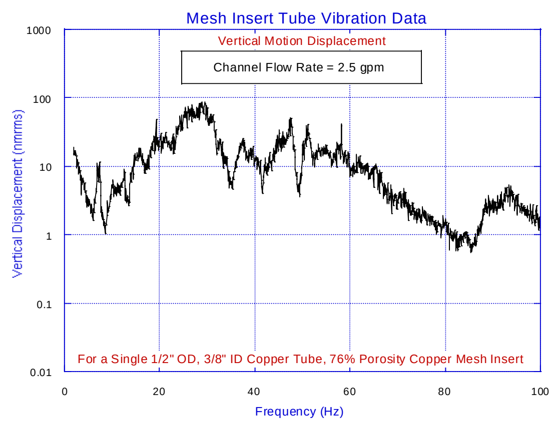
Appendix C : Plain, Open-Channel Vertical-Motion Displacement



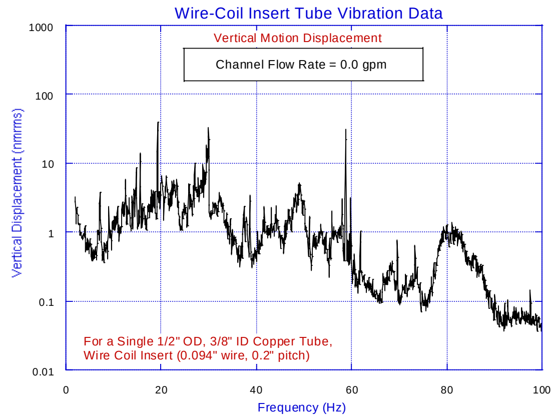


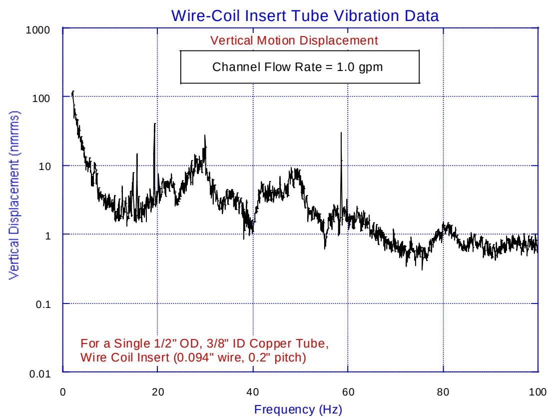


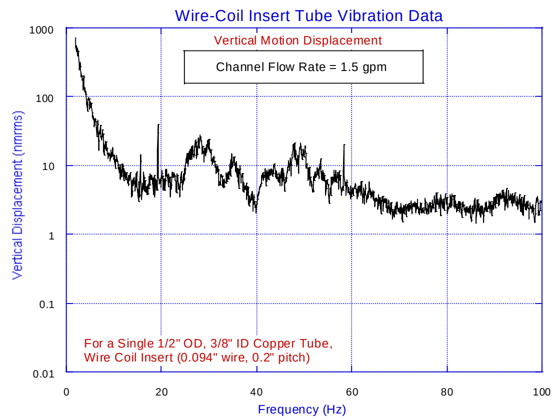


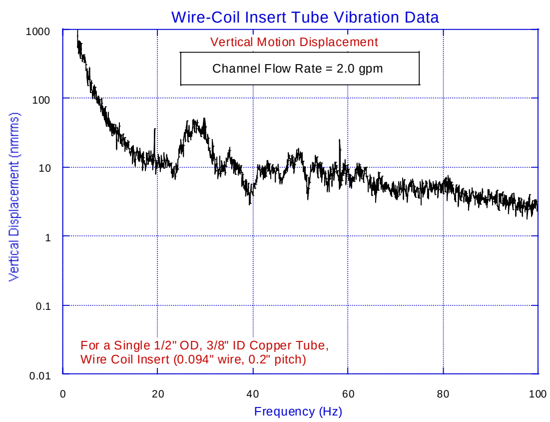


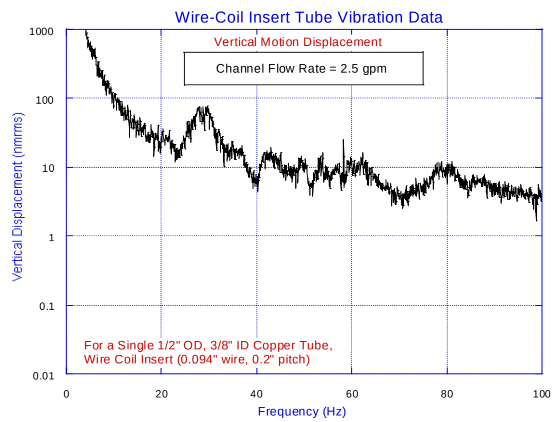
Appendix D : Copper-Mesh-Insert-Tube Vertical-Motion Displacement











Appendix E : Wire-Coil-Insert-Tube Vertical-Motion Displacement